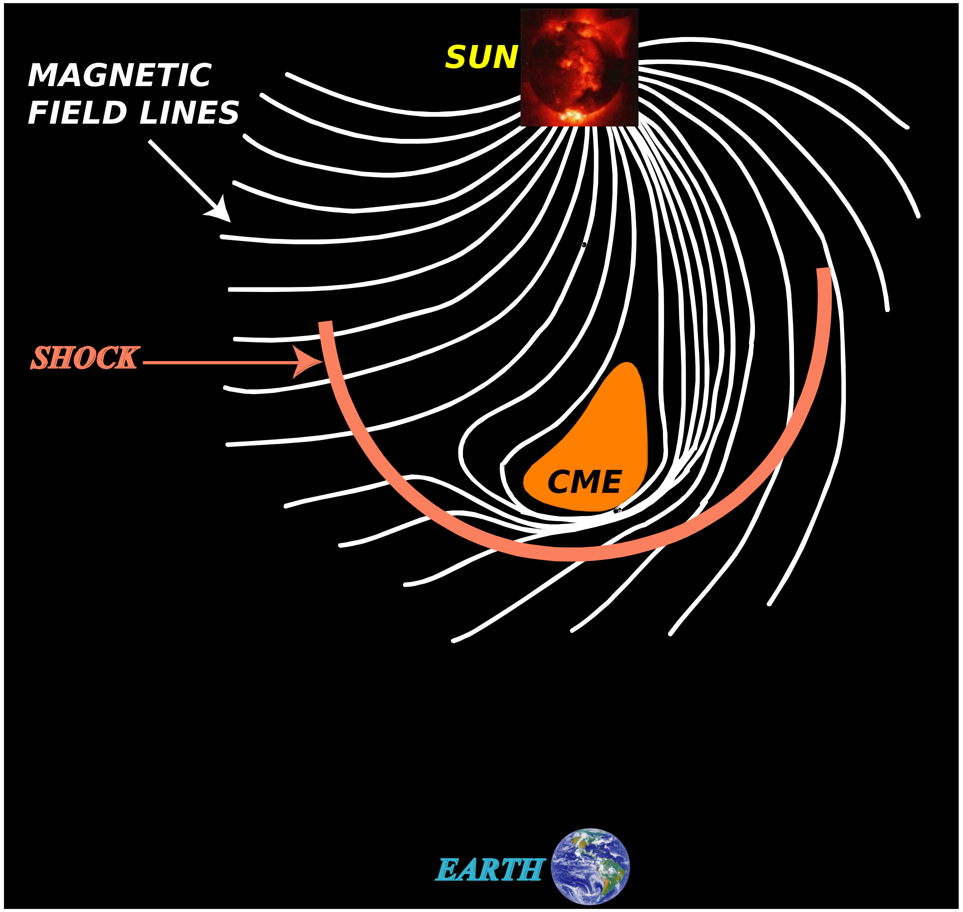
GLE events and particle acceleration at CME-driven shock



Gang Li
CSPAR/UAH

CDAW workshop II
Huntsville, Nov 16-18, 2009

Outline

- Shock Acceleration time scale

- Shock Geometry and Seed population
- Injection and its dependence on shock geometry
- NLGC Theory for Kappa_perp
- Coupling between generated waves and kappa_perp

- Composition correlation study (Mewaldt + Li)
==> a possible scenario

- Key components for GLEs: turbulence level, seed population.

- GLE as a consequence of multiple CMEs? What to look for from observation?

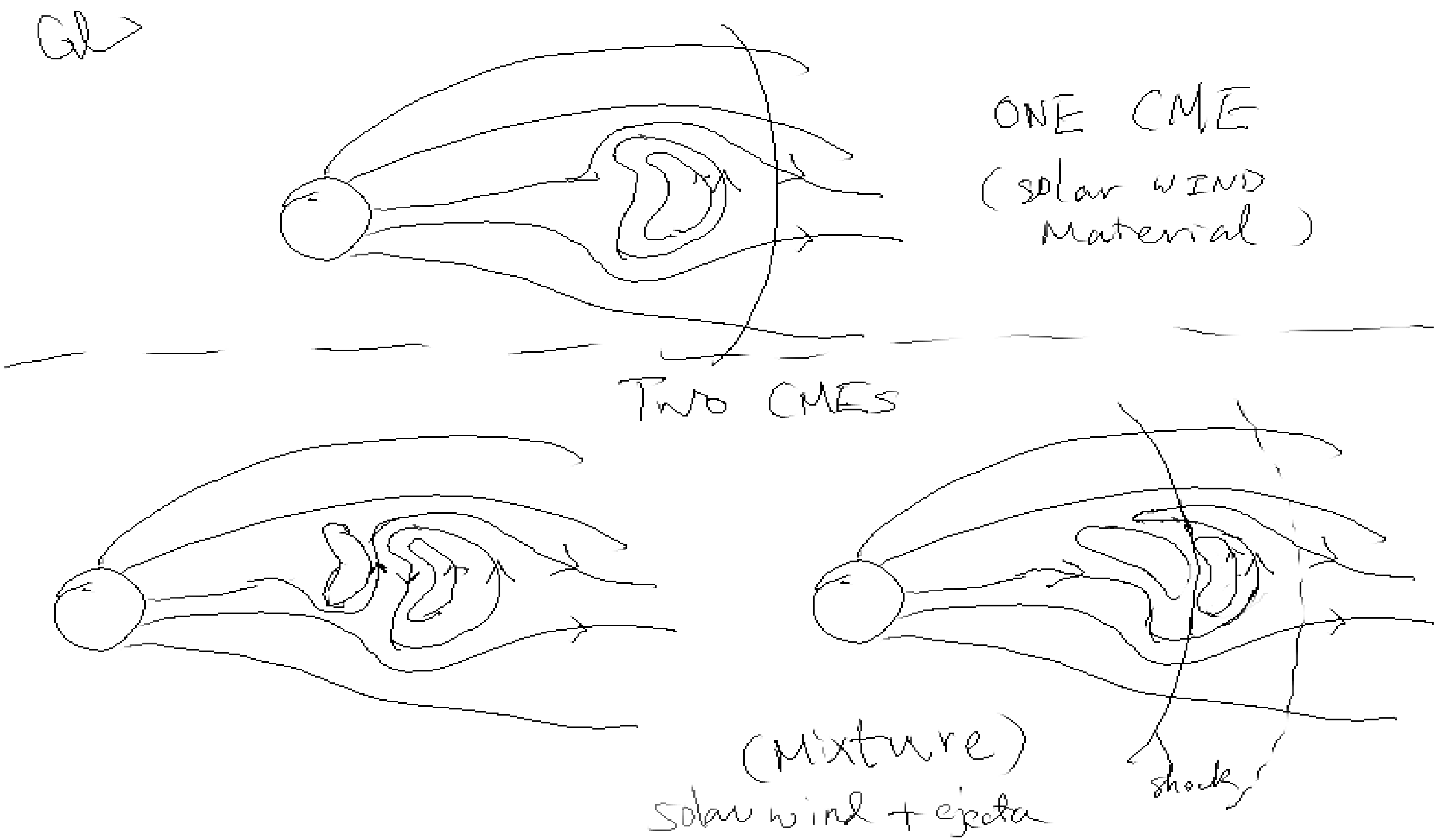
Outline – assignments from last time

- Composition correlation study (Mewaldt + Li) ==> a possible scenario [with Ron Moore]
  - Can GLE and large SEP event due to multiple CMEs? What are the favourable conditions for GLEs? What to look for from observation?

- Shock Acceleration time scale
  - Shock Geometry and Seed population
  - Injection and its dependence on shock geometry
  - NLGC Theory for Kappa_perp
  - Coupling between generated waves and kappa_perp

• Composition correlation study (Mewaldt + Li)

Last workshop: What makes up the seed population at the second shock?



Conclusion: some reconnection on a large scale is crucial !

since then

We (with Mewaldt) further considered other possible magnetic field configuration and proposed a possible scenario.

results in an ICRC (29th ICRC) proceeding paper.

Can multiple shocks trigger ground level events?

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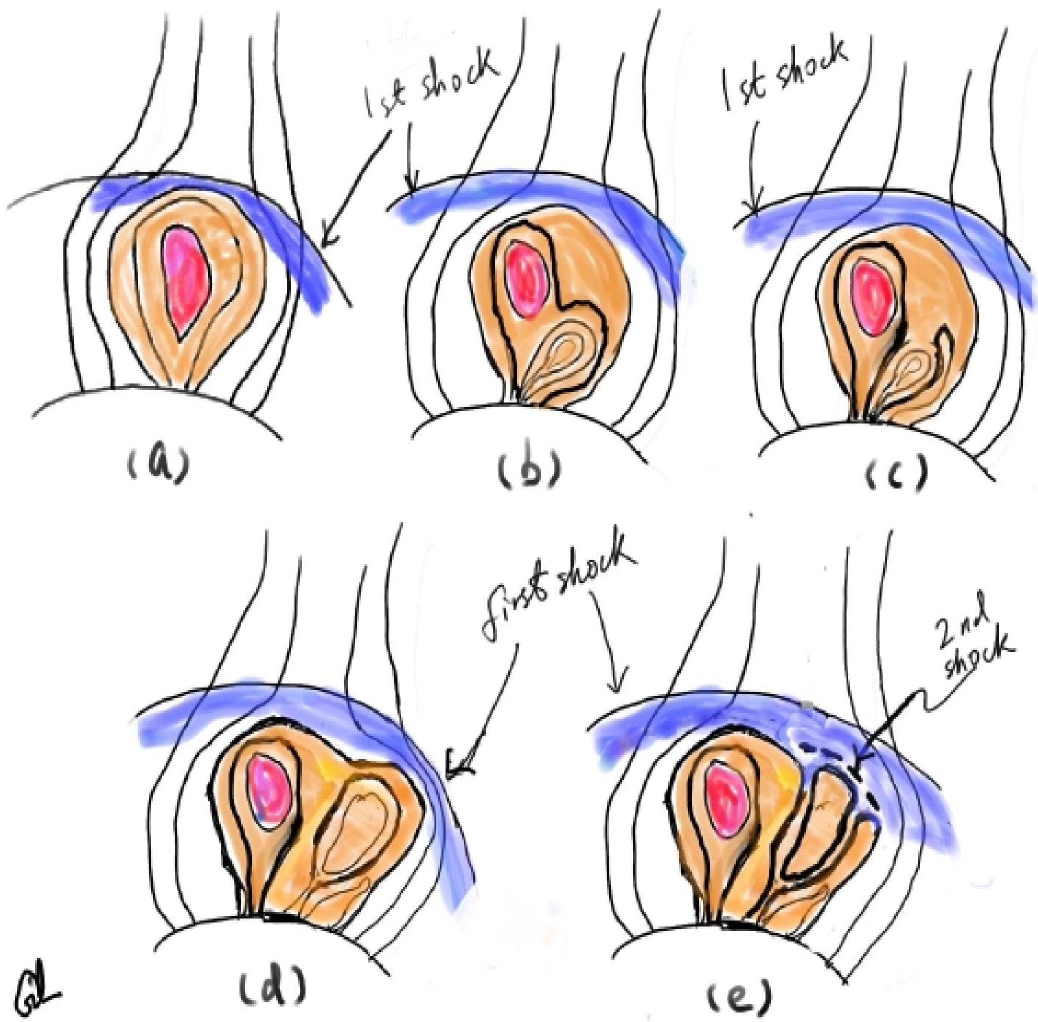
† California Institute of Technology, Pasadena, CA 91125, USA

... *We discuss here a scenario in which two CMEs occur closely in time but offset in propagation direction. We show that the resulting magnetic field configuration can lead to magnetic reconnection. This reconnection process will provide both an excess of seed population and enhanced turbulence level at the shock front of the second CME-driven shock. Enhanced particle acceleration can therefore be achieved. The implications of our proposed scenario will be discussed.*

Also in the same ICRC proceedings, Mewaldt et al. examined the composition and spectral proerperties of GLEs in Solar Cycle 23.

Cartoon No. 2



Conditions to be met in GLE events

- the second CME must occur beneath and inside the first CME (presumably both CMEs lift off from the same active region).
- the second CME must occur closely in time to the first CME.
- the second CME must be faster than the first CME.
- the second CME must propagate to a different direction from the first CME.
- the polarities (directions) of the magnetic fields enclosing the first and the second CMEs should be such that magnetic reconnection can occur.

Satisfying these conditions all at once may not be common, which suggests that GLE events should be rare, agreeing with observations.

Note: not necessarily GLE, but other large SEP events!

Since ICRC

Question one can ask:

What kind of magnetic field configuration (pre-eruption) on the solar surface are more likely to provide the reconnection?

Slide from last time *Vasyl Yurchyshyn* 's presentation

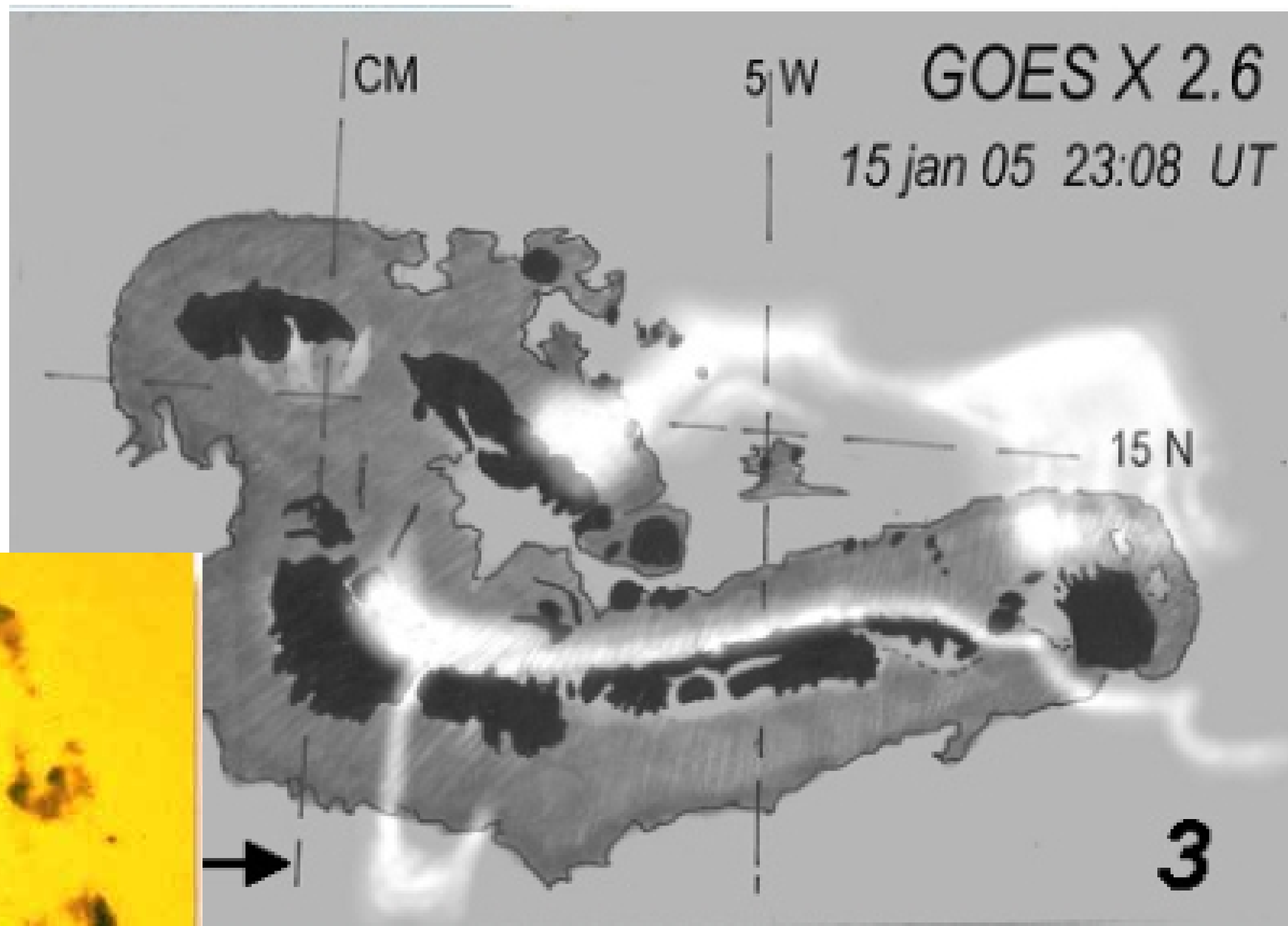
Delta spots have the highest rate of X-class flares,

	Complex Delta Spots	Single Twisted Spots	Magnetic Complexes
CMEs, #	52	15	14
ARs, #	27	14	13
<V>, km/s	1740	1490	1700
X flare, #	27	3	2
M flare, #	22	8	9
C flare, #	3	3	3

85 active region and filament associated CMEs originated in various magnetic Configurations (1997-2005)*

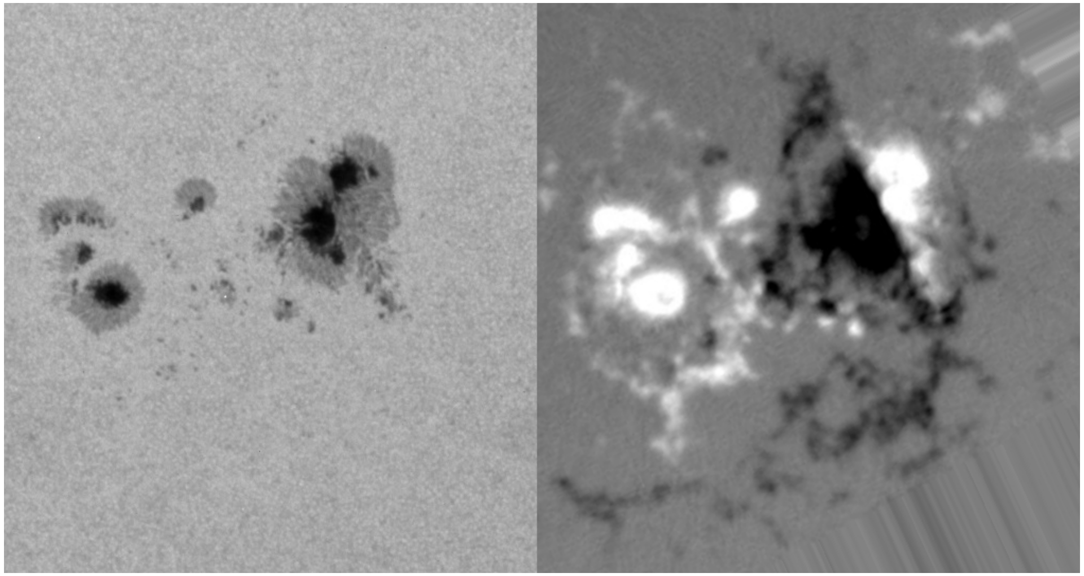
Delta Sunspots

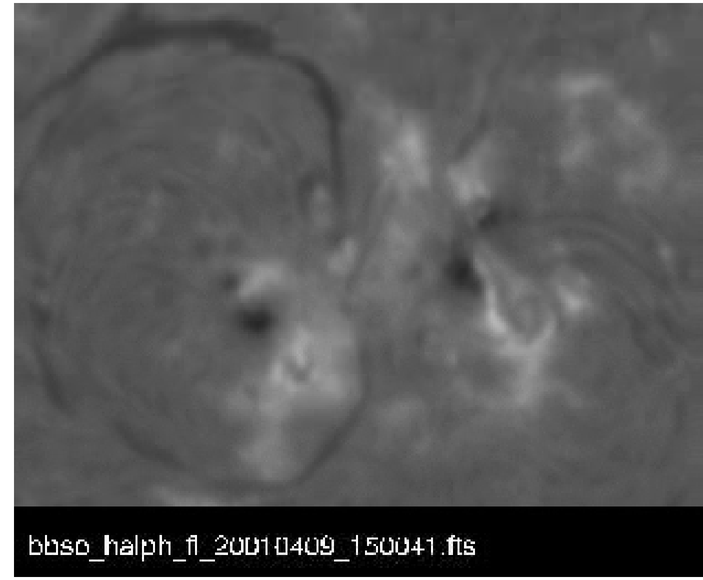
from *Vasyl Yurchyshyn* 's CDAWI presentation



drawing by Harry Roberts

AR 9415 on April 9, 2001, Source of GLE events 5 and 6





Delta Configurations - Typical features:

- two opposite polarity sunspots located in the same penumbra

- **large magnitude of the magnetic field and high horizontal gradients**

- **highly non-potential/stresses/twisted magnetic fields**

- **long neutral line w/ strong magnetic shear and gradients**

from *Vasyl Yurchyshyn* 's CDAWI presentation

Local wisdom from Ron Moore

reconnection between open and closed field lines of the first CME happen *before* the second CME, setting up the necessary composition (second CME does not play a role in reconnection).

Consider Oct. 29 event as an example.

(Ron shows his slides)

This discussion on the role of reconnection and these cartoons will be expanded and included in the final paper.

Changing Topic

- Shock Acceleration time scale

  - Shock Geometry and Seed population
  - Injection and its dependence on shock geometry
  - NLGC Theory for Kappa_perp
  - Coupling between generated waves and kappa_perp

Since last CDAW meeting,

Li et al. 8th Astrophysics Conf. Proceedings

Non-linear Guiding Center Theory and acceleration of cosmic rays at supernova remnant shocks

In that paper, we discussed the dependence of the maximum energy at a SNR shock on shock geometry using the NLGC theory. The discussion of acceleration time scale in GLE event will follow similar approach.

Why is shock geometry important?

Injection (affect the seed population) depends on shock geometry

Alfven wave amplification (turbulence level) depends on shock geometry

Total diffusion coefficient (deciding the maximum energy) depends on shock geometry

Acceleration time scale

- the highest energy is decided by the acceleration time scale.

$$\Delta t = \frac{3s}{s-1}\frac{\kappa(p)}{u_{sh}^2}\frac{\Delta p}{p}$$ Drury (1983)

$$\kappa(p) = p^{\alpha} = \kappa(p_0)(\frac{p}{p_0})^{\alpha} = \kappa_0(\frac{p}{p_0})^{\alpha}$$

$$t = \frac{3s}{s-1}\frac{\kappa_0}{u_{sh}^2}\frac{1}{\alpha}(\frac{p_i}{p_0})^{\alpha}[(p_f/p_i)^{\alpha} - 1]$$

Define p0 $$\frac{3s}{s-1}\frac{\kappa_0}{u_{sh}^2}\frac{1}{\alpha} = t$$

$$\begin{aligned} p_i &<< p_0, & p_f &= p_0, \\ p_i &\sim p_0, & p_f &= 2^{1/\alpha} p_0, \\ p_i &>> p_0, & p_f &= p_i \end{aligned}$$

If $\lambda \sim p^{1/3}$, $\alpha = 4/3$.

$$(p_0/p_i)^{\alpha} = [(p_f/p_i)^{\alpha} - 1]$$

$$p_f/p_i = (1 + (p_0/p_i)^{\alpha})^{1/\alpha}$$

p0 defines the highest accelerated momentum when the injection momentum is small. p0 is decided by the acceleration time scale.

Bottom line: need accurate description of κ!

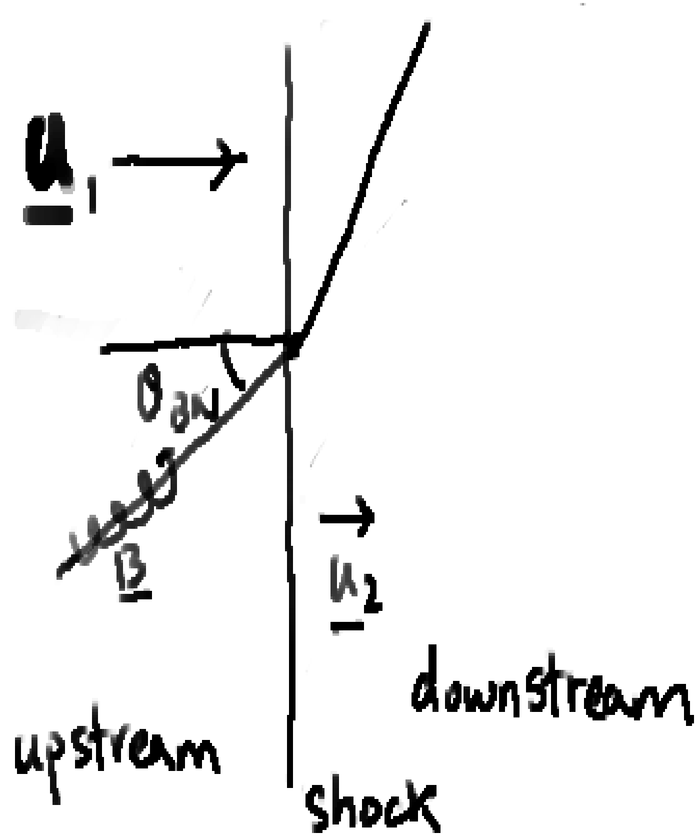
1) Injection

For particles to be diffusively accelerated at the shock, it must be able to cross the shock multiple times.

Clearly, the efficiency of multiple crossing depends on ptcl's initial energy and pitch angle. A test particle calculation or a PIC simulation is needed to obtain the detailed information of the injection efficiency.

However, a reasonable estimate can be obtained as follows

$$v > \alpha u / cos(\theta_{BN}),$$

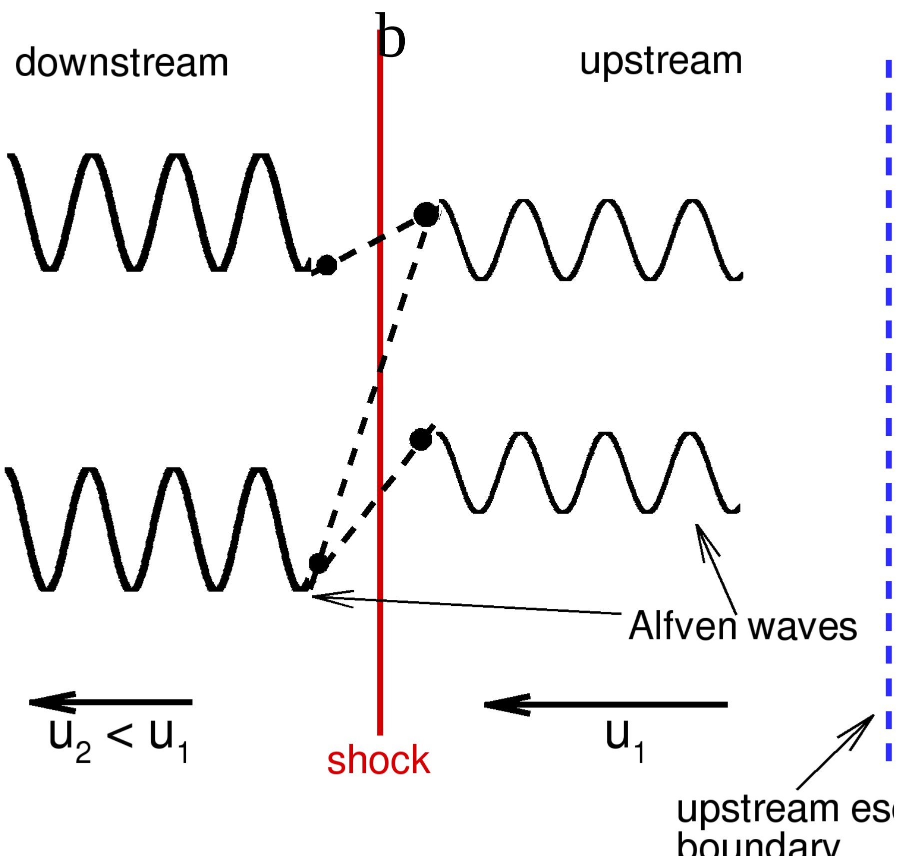


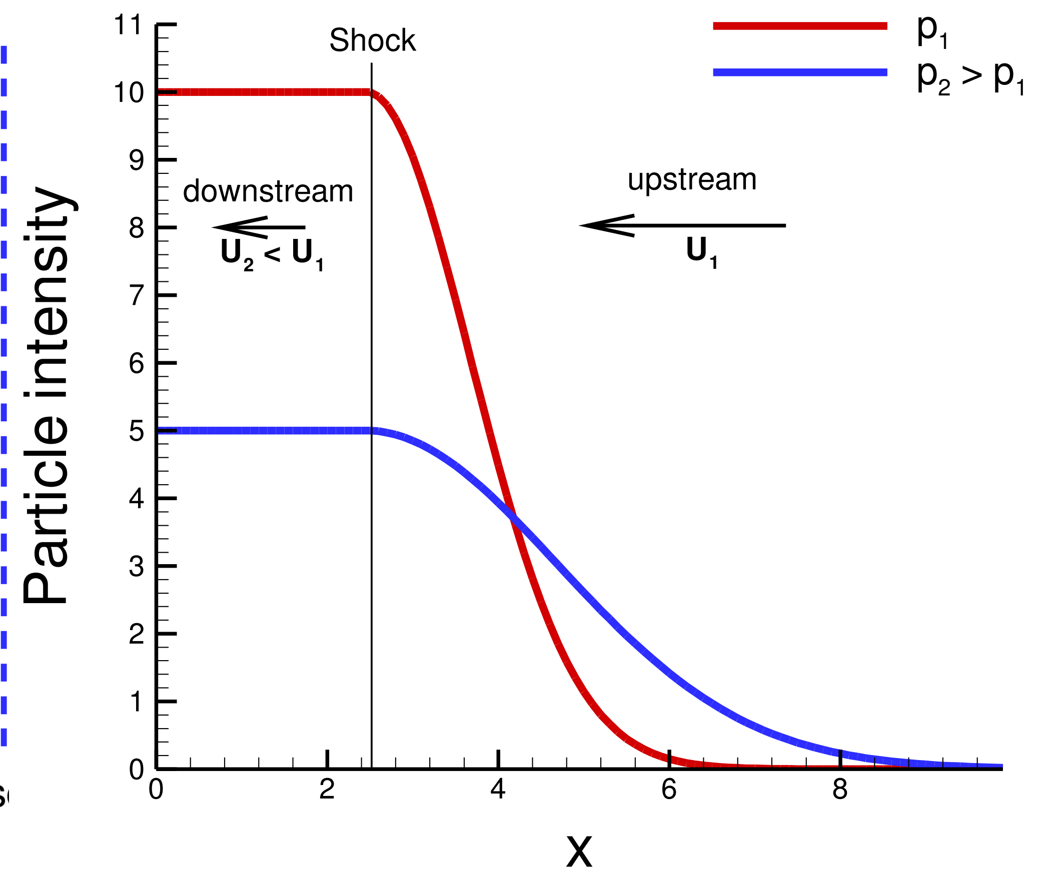
Physical meaning of this equation is that when ptcl's projected speed is larger than the upstream plasma speed, it will have enough speed to stay in front of the shock and undergo multiple scattering.

Adopt this condition in this work

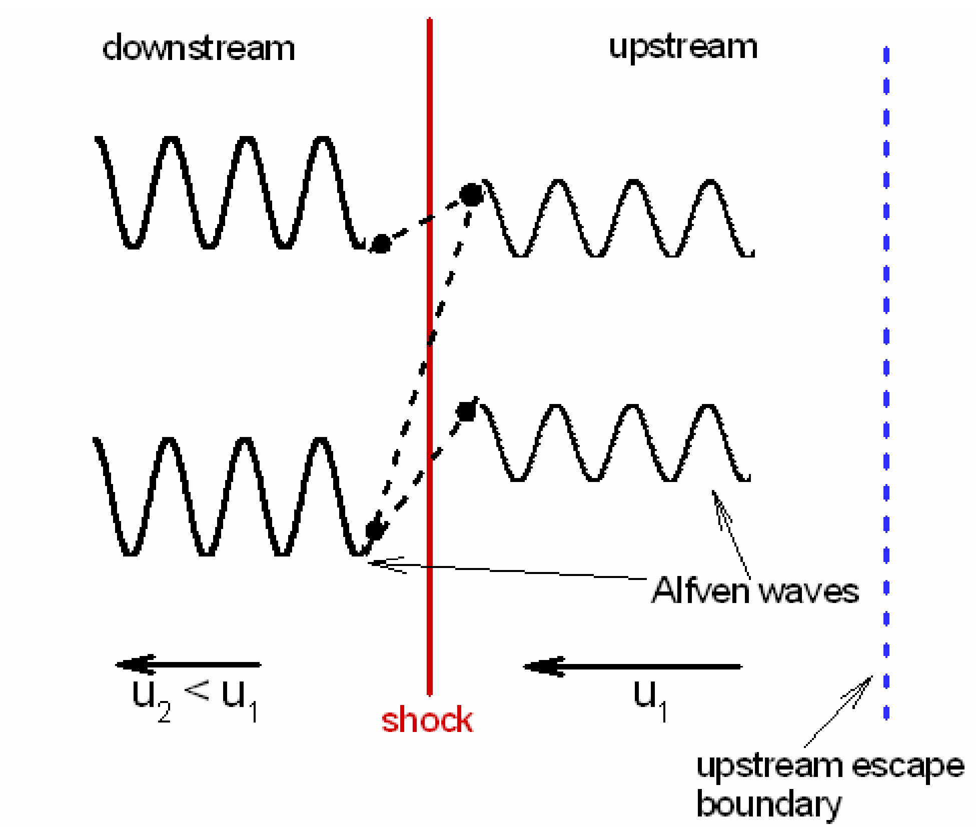
2) Alfven wave generation at quasi-parallel shock

Wave generation is due to streaming protons





Generation of Alfven waves at Quasi-parallel shock via streaming ions



Out-streaming protons drive Alfven waves, which grows as,

$$\frac{\partial A}{\partial t} + u\frac{\partial A}{\partial r} = \Gamma A - \gamma A,$$

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial r} - \frac{p}{3}\frac{\partial u}{\partial r}\frac{\partial f}{\partial p} = \frac{\partial}{\partial r}\left(\kappa\frac{\partial f}{\partial r}\right),$$

$$\kappa(p) = \frac{\kappa_0}{A(k)}\frac{B_0}{B}\frac{(p/p_0)^2}{\sqrt{(m_p c/p_0)^2 + (p/p_0)^2}},$$

$$I_+(|k| < \gamma m|\Omega|/p_o) = \frac{q|\Omega|NV_A p_o^{q-3} cos\psi}{4(q-4)(q-2)V'^2}\frac{1}{k^2}\left|\frac{\gamma m\Omega}{k}\right|^{4-q} + I_+^o(k)$$

Doppler condition: $k \approx \gamma m\Omega|\mu|/\mu p.$ $\Omega = (Q/A)eB/\gamma m_p$

Complicated θ dependence

through wave
propagation direction

Through particle injection

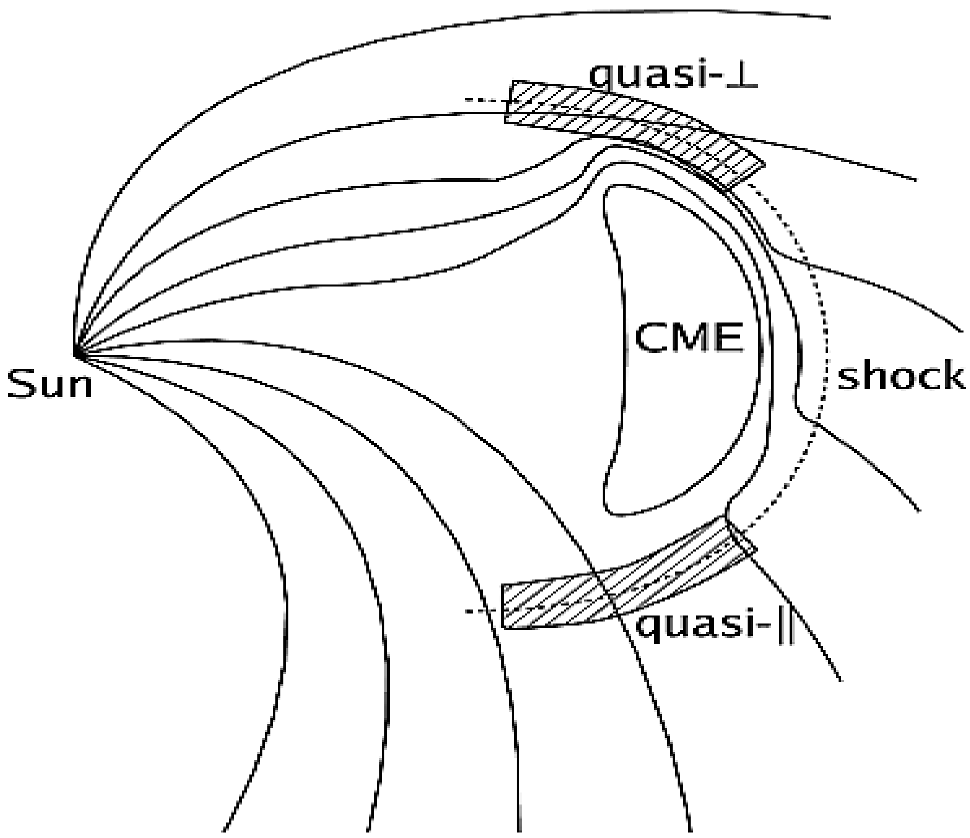
$$I_+(|k| < \gamma m|\Omega|/p_o) = \frac{q|\Omega|\boxed{N}V_A p_o^{q-3}\boxed{cos\psi}}{4(q-4)(q-2)V'^2}\frac{1}{k^2}\left|\frac{\gamma m \Omega}{k}\right|^{4-q} + I_+^o(k)$$

If f(E) of the seed population is f (E) ~ $E^{-\gamma}$, then

I(k) has a cos (θ) $^{2(\gamma-1)}$ dependence.

3) NLGC theory and kappa_perp oblique shock is necessary

$$\kappa_{xx} = \kappa_{\perp} \sin^2\theta_{bn} + \kappa_{\parallel} \cos^2\theta_{bn}$$



CME shock is dynamic – evolving with time and changing geometry along the shock surface.

The acceleration time scale depends on the total kappa

Non-linear Guiding Center Theory and its key assumptions

$$\kappa_{ij} = \int_0^t \langle v_j(0) v_i(t') \rangle dt'$$

Need to find an approximation for the correlation function!

Matthaeus et al (2003)

$$\tilde{v}_x \equiv a v_z b_x / B_0,$$

The value of a can be obtained, see Salchi & Dosch (2007)

$$\langle v_z(0) b_x[x(0), 0]\, v_z(t') b_x[x(t'), t'] \rangle = \langle v_z(0) v_z(t') \rangle \langle b_x[x(0), 0]\, b_x[x(t'), t'] \rangle$$

$$\boxed{\kappa_{xx} = \frac{a^2}{B_0^2} \int_0^\infty dt' \langle v_z(0) v_z(t') \rangle \langle b_x[x(0), 0] b_x[x(t'), t'] \rangle.}$$

Non-linear Guiding Center Theory and its key assumptions (2)

$$\langle b_x[x(0),0]\, b_x[x(t'),t']\rangle = \int R_{xx}(y,t')\, P(y|t')\, d^3 y,$$

two point correlation, related to power spectrum

random variable, diffusion == > a Gaussian distribution

can be extended to a more general Chapman Kolmogorov approach (Webb et al. 2006)

$$P_\perp(x,y,t|x_0,y_0,t_0) = \int_{-\infty}^{\infty} dz\, P_{FRW}(x,y|z;x_0,y_0,z_0)\, P_{p\|}(z,t|z_0,t_0)$$

Coupling to $\lambda_{\parallel}$

The coupling to the motion in the parallel direction is through,

$$\langle v_z(0) v_z(t') \rangle = (v^2/3) e^{-vt'/\lambda_{\parallel}}$$

Again, a diffusion in the parallel direction at late time is assumed.

However, the exact functional form of an exponential is NOT necessarily the BEST choice.

===> $$\kappa_{xx} = \frac{a^2 v^2}{3} \int d^3k \left[\frac{S_{xx}(\boldsymbol{k})}{B_0^2} \int_0^{\infty} dt' \, e^{-vt'/\lambda_{\parallel}} \Gamma_{xx}(\boldsymbol{k}, t') \langle e^{i\boldsymbol{k}\cdot\boldsymbol{x}(t')} \rangle \right]$$

Non-linear Guiding Center Theory and its key assumptions

Diffusion in both directions:

$$\left\langle e^{i\mathbf{k}\cdot\mathbf{x}(t')}\right\rangle = e^{-k_\perp^2\kappa_{xx}t' - k_\parallel^2\kappa_{zz}t'},$$

2D - component of the turbulence

$$\kappa_{xx} = \frac{a^2 v^2}{3B_0^2}\int \frac{S_{xx}(\mathbf{k})\,dk_x\,dk_y\,dk_\parallel}{\frac{v}{\lambda_\parallel} + (k_x^2 + k_y^2)\kappa_{xx} + k_\parallel^2\kappa_{zz} + \gamma(\mathbf{k})}$$

Non-linear

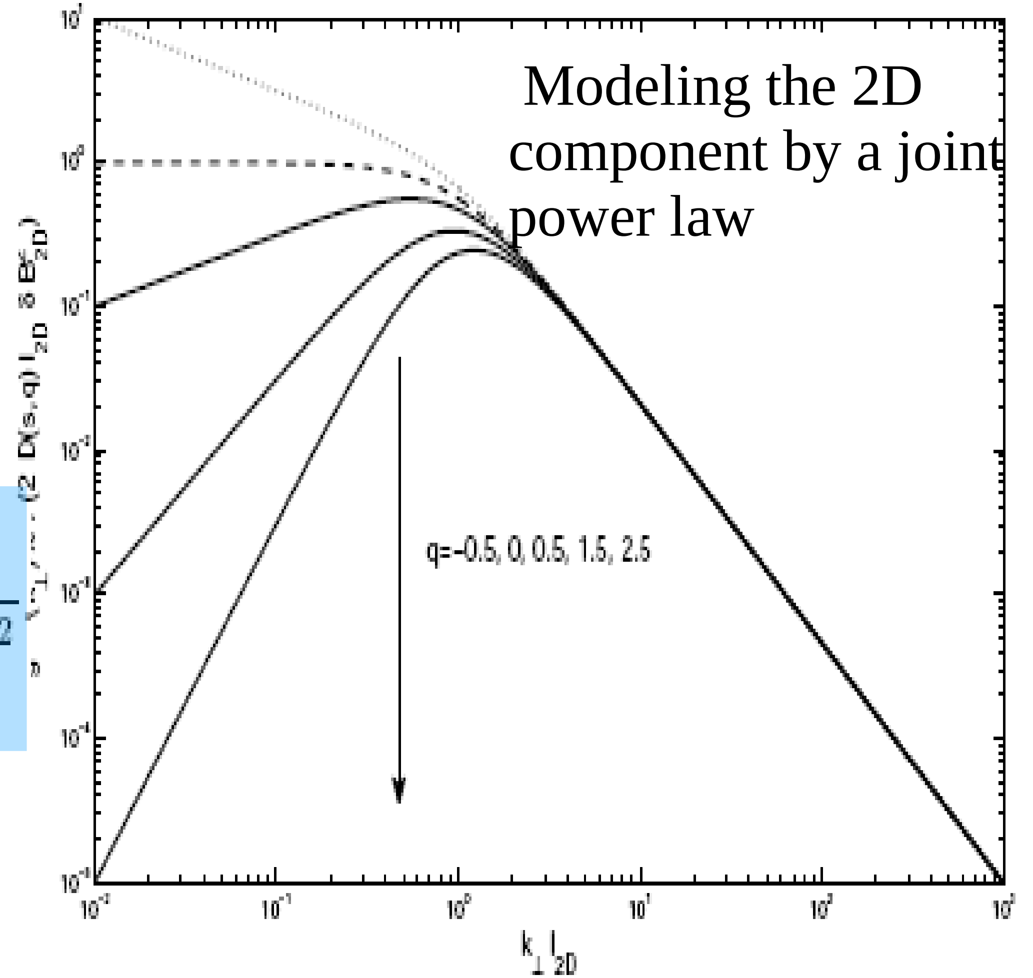
Coupling to the parallel direction

Power spectrum of the 2D component

Magnetic field is divergence free

$$P^{2D}_{lm}(\vec{k}) = g^{2D}(k_\perp)\frac{\delta(k_\parallel)}{k_\perp}\boxed{\left[\delta_{lm} - \frac{k_l k_m}{k^2}\right]}, \quad l,m = x,y$$

$$\frac{\delta B^2_{2D} l_{2D}}{\pi}\;\frac{\Gamma\left(\frac{s+q}{2}\right)}{\Gamma\left(\frac{s-1}{2}\right)\Gamma\left(\frac{q+1}{2}\right)}\;\frac{(k_\perp l_{2D})^q}{[1+(k_\perp l_{2D})^2]^{(s+q)/2}}$$



Salchi, Li and Zank (2009)

l_{2D} : bent over scale

$\lambda_\perp$ as a function of $\lambda_\parallel$ and l_{2D}

From Salchi, Li and Zank (2009)

$$\frac{\lambda_\perp}{\lambda_\parallel} = a^2 D(s,q)\epsilon \frac{\delta B_{2D}^2}{B_0^2} I(\epsilon, s, q)$$

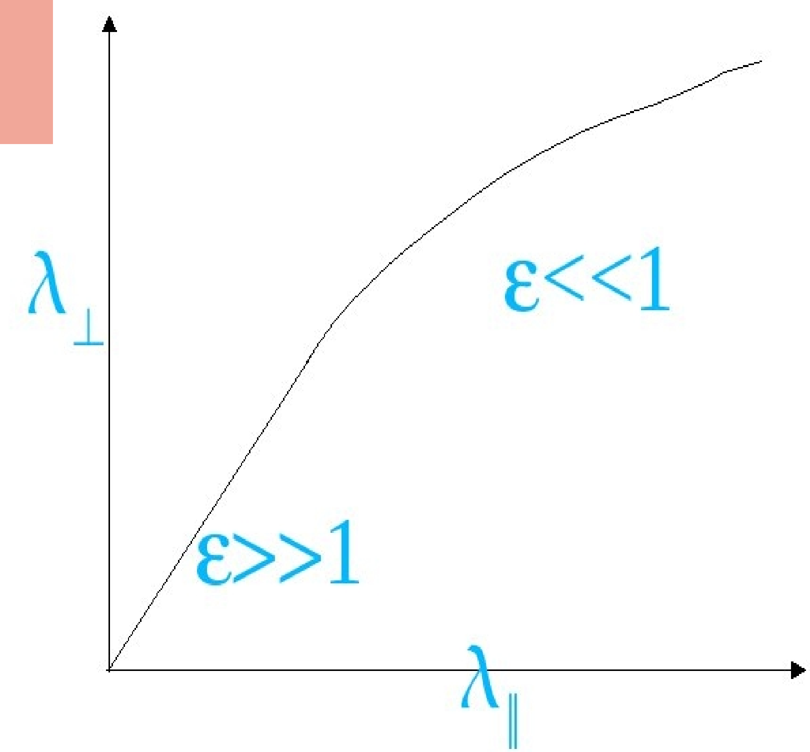
with

$$I(\epsilon, s, q) = 2\int_0^\infty dx\, x^q (1+x^2)^{-(s+q)/2}(\epsilon + x^2)^{-1}.$$

$$\epsilon = \frac{3 l_{2D}^2}{\lambda_\parallel \lambda_\perp}$$ is the control parameter

If $\varepsilon >> 1$, $\lambda_\perp \sim \lambda_\parallel$

If $\varepsilon << 1$, $\lambda_\perp \sim l_{2d}^{(2q+2)/(q+3)} \lambda_\parallel^{(1-q)/(q+3)}$



Bottom line (conclusion of the paper):

the acceleration time scale, and therefore the maximum energy at a shock has a strong dependence on θ.

The conclusion that a quasi-perp shock can accelerate particles to higher energies is NOT justified.

Using the NLGC theory, we can explore numerically the acceleration time scale and the maximum energy at a CME-driven shock.

Some tasks remain to be done:

1) the injection efficiency

2) evaluation of kappa as a function of theta_BN using NLGC theory.

3) How does the upstream wave intensity vary as a function of theta_BN (perhaps at Earth's Bow shock).

Backups

κ in perpendicular shocks – NLGC theory

At a quasi-perp. shock, Alfven wave intensity goes to zero, so contribution of $\kappa_{\|}\cos(\theta)$ can be ignored. The major contribution comes from $\kappa_{\perp}$.

Need a good theory of $\kappa\perp$

Simple QLT: $\kappa_{\perp} = \kappa_{\|} /[1 + (\lambda_{\|} / rl)^2]$ Jokippi 1987

Non-linear-Guiding-center:

$$\boxed{\kappa_{\perp}} = \frac{a^2 v^2}{3B^2}\int_0^{\infty} \frac{S_{\perp}(\mathbf{k})d^3\mathbf{k}}{v/\lambda_{\|} + k_{\perp}^2 \boxed{\kappa_{\perp}} + k_{\|}^2 \kappa_{\|}}.$$

Matthaeus et al 2003

$$\lambda_{xx} ; \left(\sqrt{3}\pi\, a^2 C\right)^{2/3} \left[\frac{\langle b_{2D}^2\rangle}{B_0^2}\lambda_{2D}\right]^{2/3} \lambda_{\parallel}^{1/3} \left[1+\frac{\left(a^2 C\right)^{1/3}}{\left(\sqrt{3}\pi\right)^{2/3}}\frac{\langle b_{slab}^2\rangle}{\langle b_{2D}^2\rangle^{2/3}\left(B_0^2\right)^{1/3}}\frac{\min\left(\lambda_{slab},\lambda_{\parallel}/\sqrt{3}\right)}{\lambda_{slab}^{2/3}\lambda_{\parallel}^{1/3}}\left(4.33H\left(\lambda_{slab}-\lambda_{\parallel}/\sqrt{3}\right)+3.091H\left(\lambda_{\parallel}/\sqrt{3}-\lambda_{slab}\right)\right)\right]^{2/3}$$

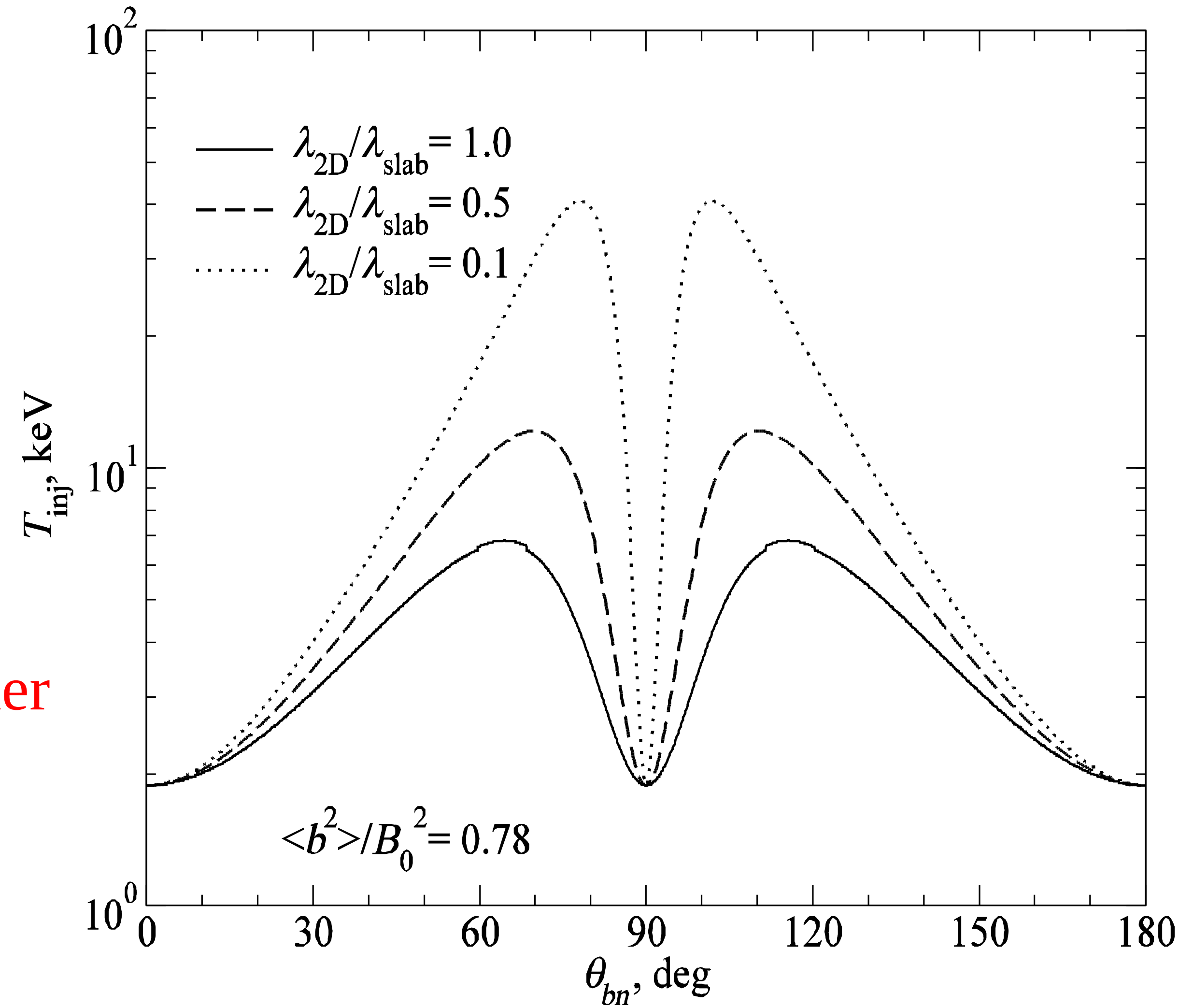
Zank et al 2004

Anisotropy and the injection threshold

diffusive shock acceleration assumes isotropic distribution f

➔

$$\xi = s / f\, v \;<=1$$

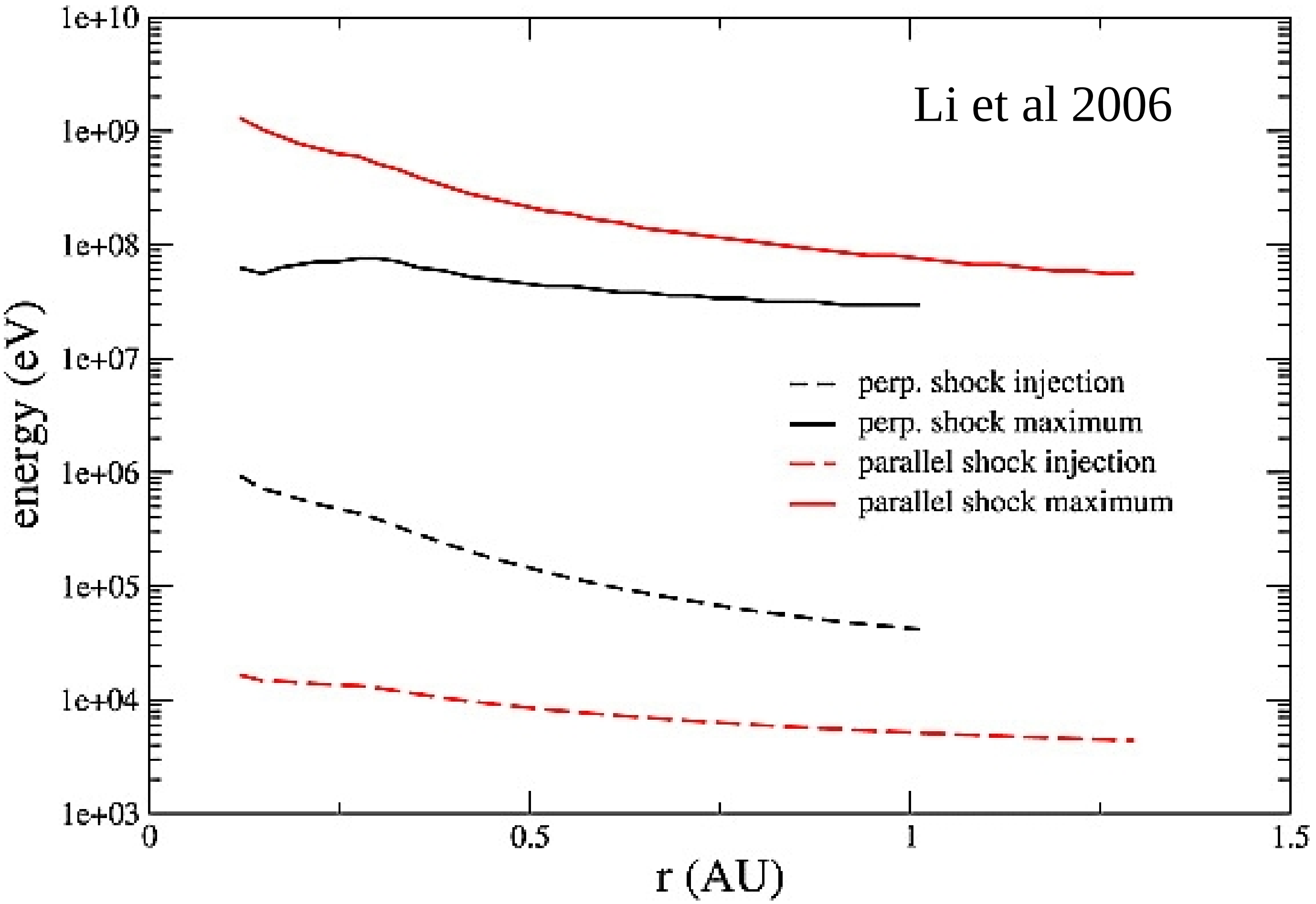


Perpendicular shock has a higher injection threshold!

$$\xi = \frac{3u}{v}\left[\left(\frac{q}{3}-1\right)^2 + \frac{(\kappa_d^2 + \kappa_\parallel^2 \cos^2\theta_{bn})\sin^2\theta_{bn}}{(\kappa_\perp \sin^2\theta_{bn} + \kappa_\parallel \cos^2\theta_{bn})^2}\right]^{1/2}$$

Remark: Isotropic assumption for diffusive shock acceleration may not be necessary.

Maximum energy for quasi-parallel and quasi-perp. shocks



- Ignore the change of shock geometry during shock propagation.
- Consider a parallel shock and a quasi-perp. Shock (85 degree).
- parallel with a strong turbulence reaches a higher energy than a quasi-perp shock.
- Perp. shock requires higher injection

Pre-turbulence -- Multiple CMEs

If one-stage rocket can not send us to the Moon (Mars), then use multiple stage rocket. (Van Braun must have said this)

If one CME can not accelerate particles to very high energies, may be multiple CMEs can?

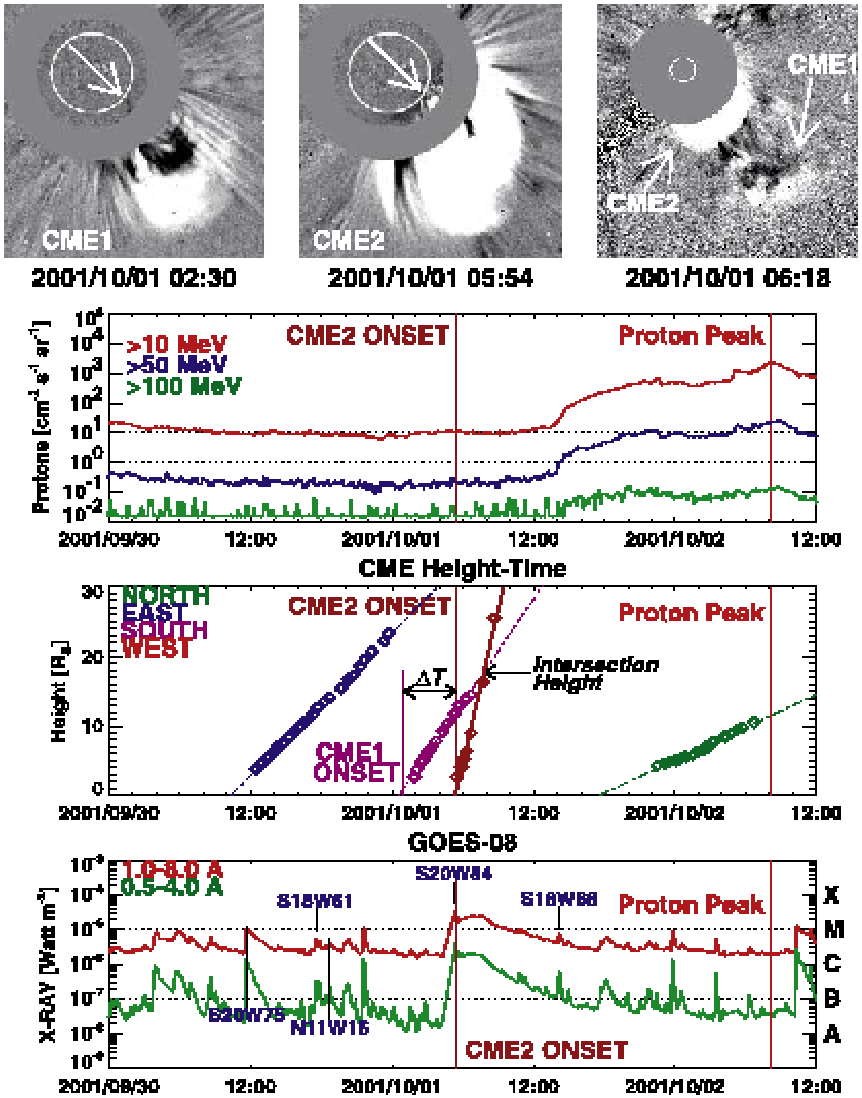
Need to be careful: increase is not linear, but log.

Observational hints:

- Individual large SEP events at 1 AU may correspond to multiple CMEs near the Sun. (Lyon and Simnett, 1999). If a CME travels faster than one or several preceding CMEs, there will be CME intersections. Something interesting may happen.

- Correlation between multiple CME and large SEP events. (Gopalswamy et al. JGR, 2004)

Pre-turbulence -- Multiple CMEs



Gopalswamy et al. JGR, 2004

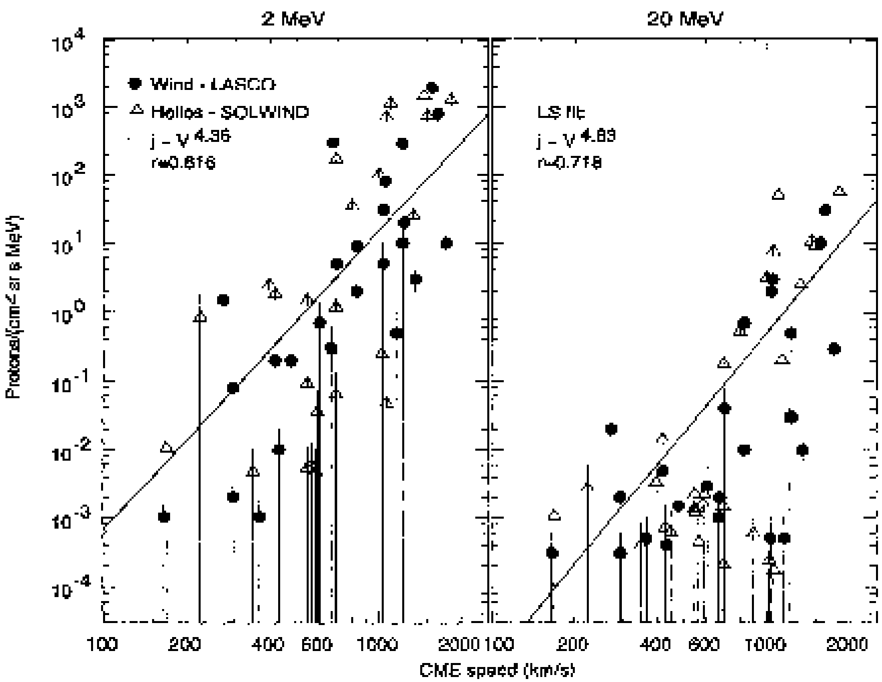
total of 57 events between 1996-2002 are selected, with intensity > 10 pfu (proton cm-2 s-1sr-1) at >10 MeV channel.

23 with preceding CMEs (within 1 day), 20 without preceding CMEs

Conclusion: <u>Higher SEP intensity results whenever a CME is preceded by another wide CME from the same source region. And the correlation between the peak intensity and the CME speed is improved substantially over earlier work (Kahler, 2001).</u>

Correlation of intensity with CME shock speed

Reames, AIP conf. 516, 2001



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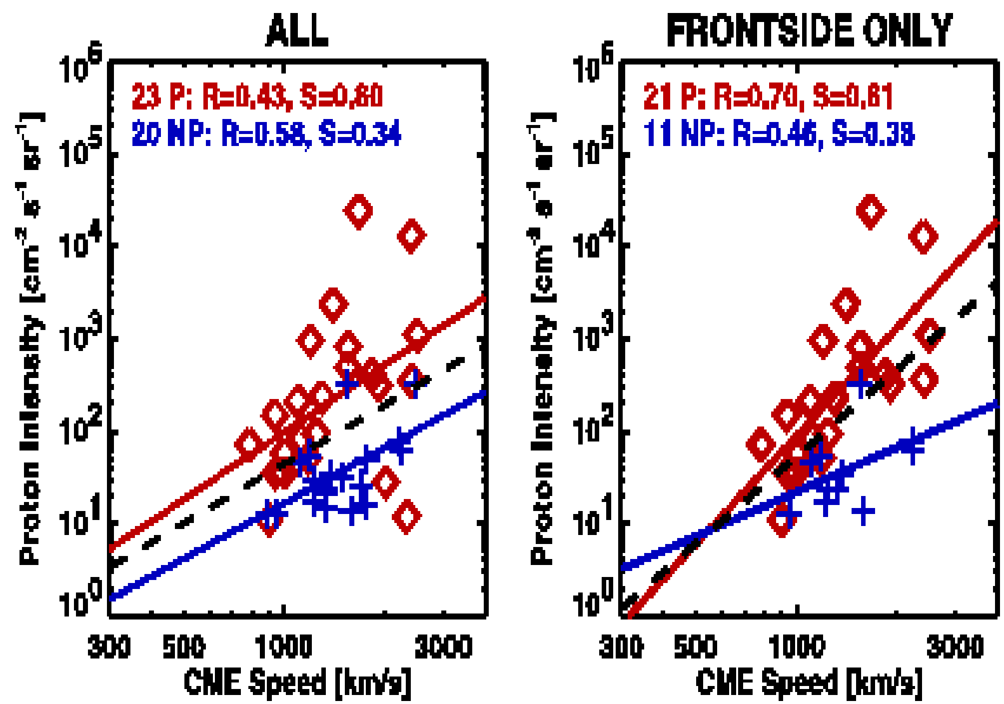
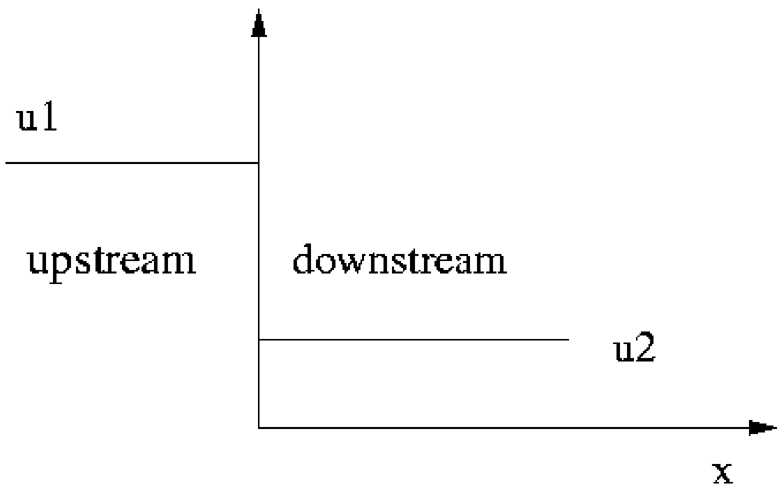


Old data from WIND, IMP-8, Helios.

Peak intensity at 2 MeV and 20 MeV.

CMEs with and w/o preceding CMEs are clearly separated. Particle intensities w/o preceding shocks are generally smaller.

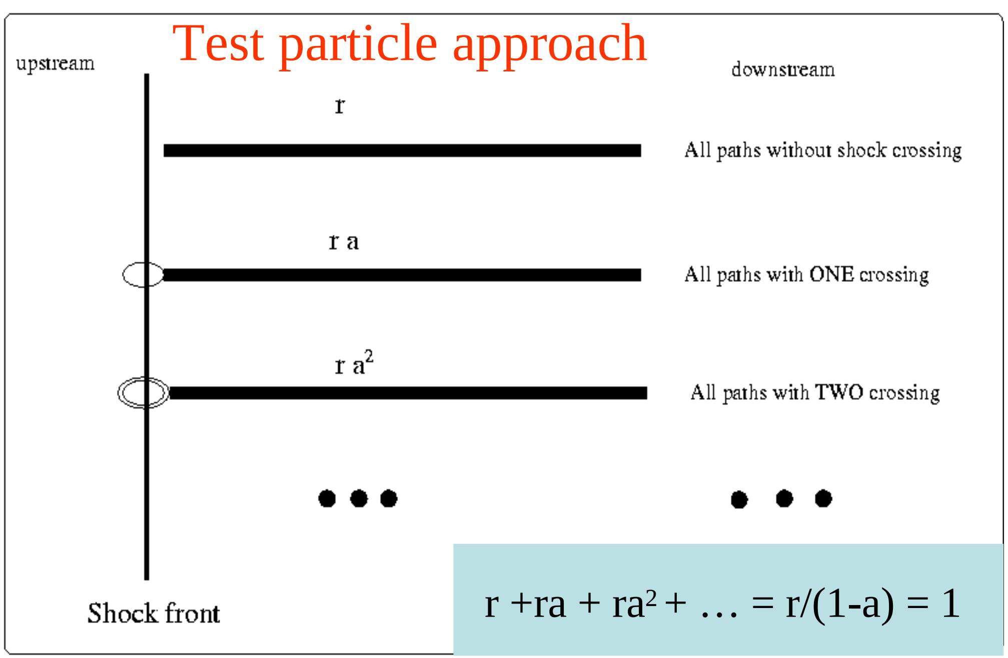
Shock acceleration in a Nutshell



- 1-D case and x-independent u and κ.
- matching condition, both f and current s continues.

$$S = \frac{-1}{3}\frac{\partial ln f}{\partial ln p} - \kappa \frac{\partial f}{\partial x}$$

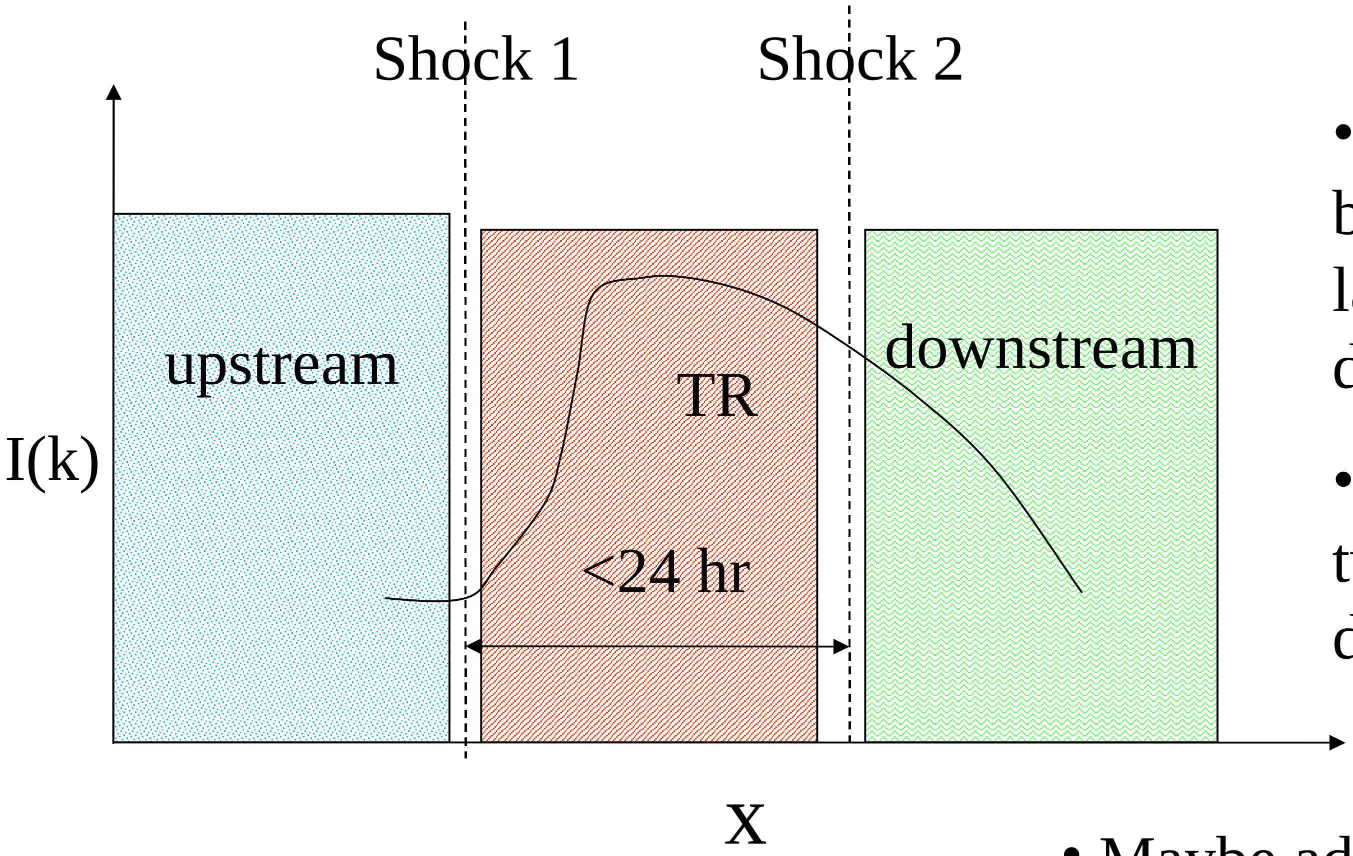
$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} - \frac{\partial}{\partial x}\left(\kappa \frac{\partial f}{\partial x}\right) - \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} = 0$$



$$\boxed{f(p) \sim p^{-3s/s-1}}$$

Power law spectrum, spectral index only depends on compression ratio s!

Complication of reality

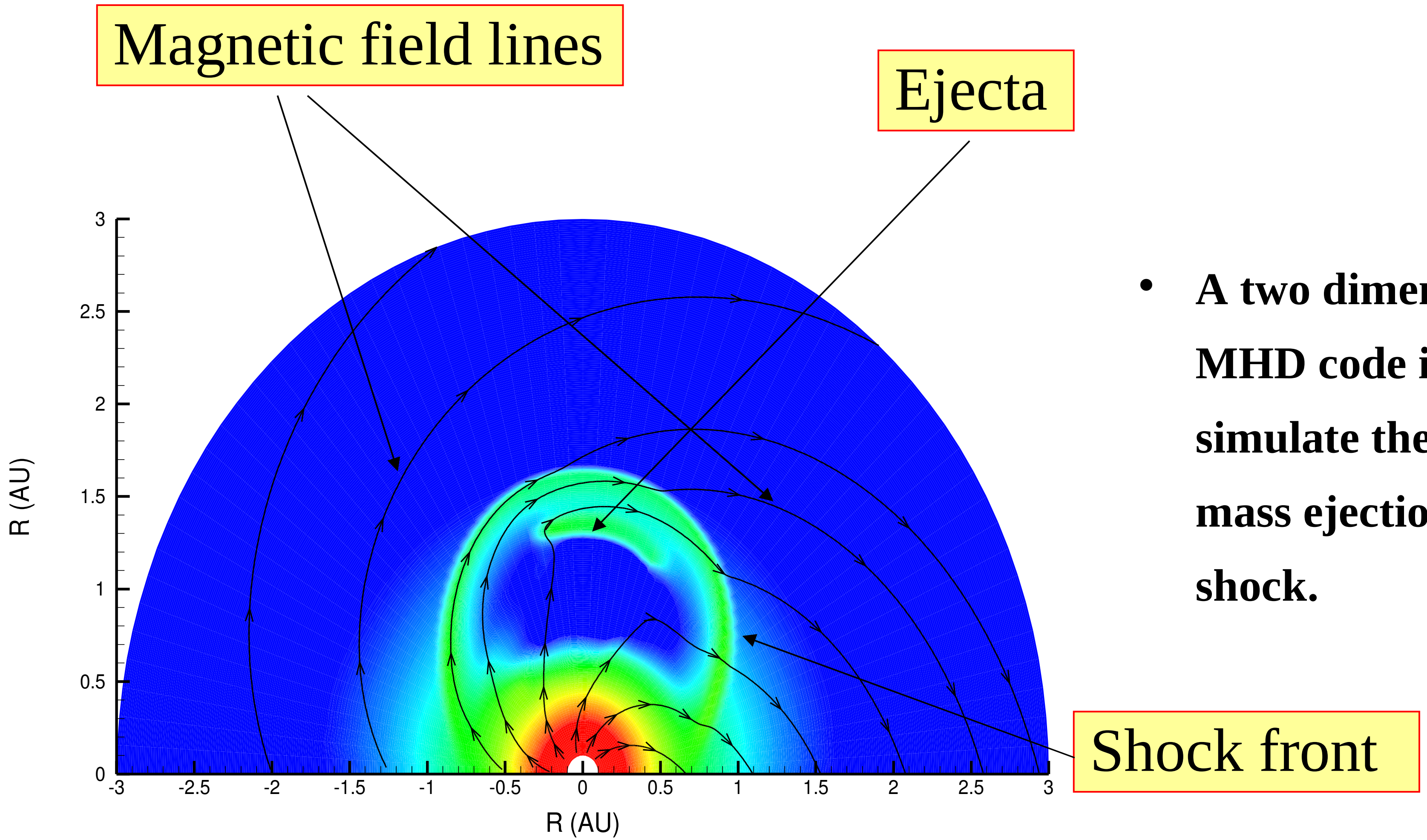


- If the separation between two shocks is too large, the turbulence may drop to background level.
- Mean free path between two shocks should be x-dependent.

TR: Turbulent Region

- Maybe additional acceleration between the two shocks?

Two-dimensional model



- **A two dimensional MHD code is used to simulate the coronal mass ejection driven shock.**

Particle intensities at 1 AU

The intensity profiles observed at 1 AU depend on the position of the CME relative to the observed.

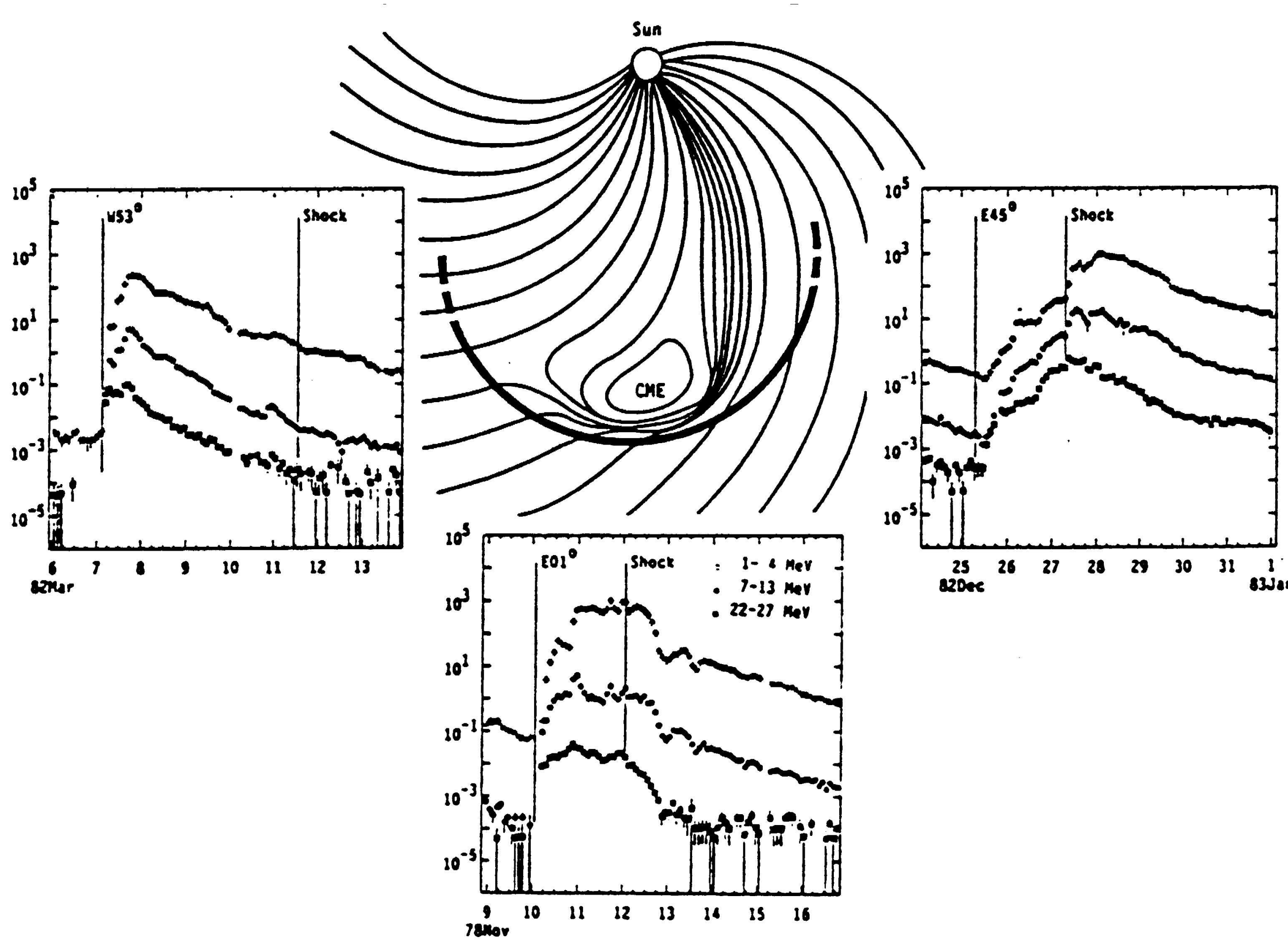


Figure from Reames, 1999.

Characteristics of Large SEP Events

- **<u>Infrequent:</u>** ***~5 - 10 large events/year in solar-active years. Associate with fast CME-driven Shocks (top 1-2%) and/or large flares.***
- **<u>Energetic</u>***: 10 keV < K < 10 GeV*
- **<u>Power law spectrum:</u>** ***reasonably "universal ".***
- **<u>High intensity</u>: *intensity > 10 pfu (proton cm-2 s-1sr-1) at >10 MeV channel (corresponding to 10^2 – 10^6 increase depending on energy)*.**
- **<u>Composition:</u>** ***electrons, protons, heavy ions***.

<u>First order Fermi acceleration?</u>

problems:

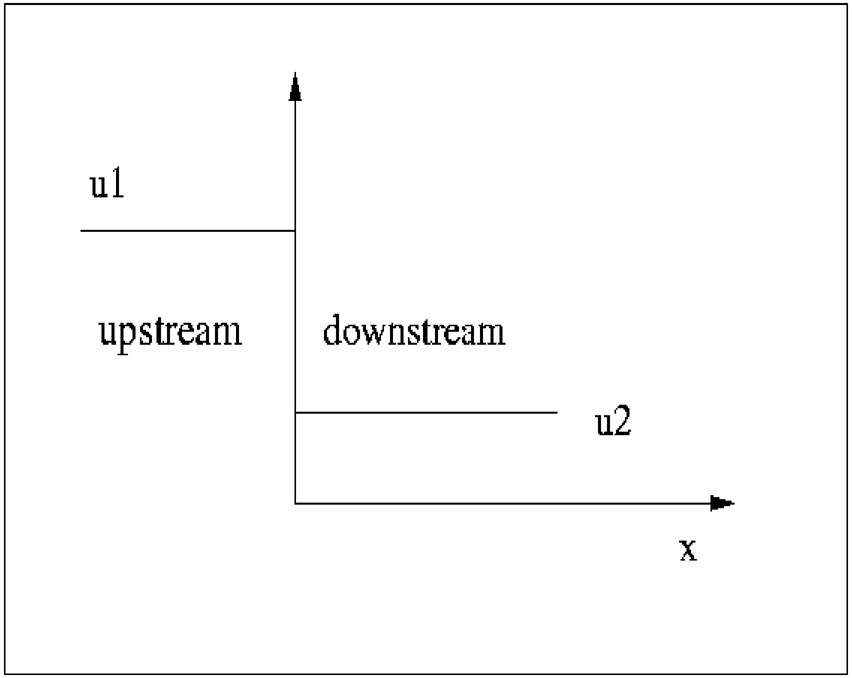
Strong shocks not always lead to SEP

Spectral and abundances variability

Answers?

- Shock geometry?
- *Pre-existing turbulence?*

Fermi acceleration and time scales



$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} - \frac{\partial}{\partial x}\left(\kappa\frac{\partial f}{\partial x}\right) - \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} + \boxed{\frac{f}{\tau}} = \frac{f_\infty}{\tau_\infty}$$

$$f = \begin{cases} A(p) & \text{downstream} \\ B(p)exp[(u/\kappa)(1+\delta)x] & \text{upstream} \end{cases}$$

$$\delta = \frac{-1+\sqrt{1+4\alpha\kappa/u_1^2}}{2}$$

$$f(p) \sim p^{-(1+\delta)[3s/s-1]}$$

steady state, with boundary conditions:

a) f ->0 at the upstream boundary.

b) f = some non-zero value at down stream boundary.

Li et al 2005

τ~ loss time scale

$\tau_{acc} \sim \kappa/u_1^2$ acceleration time scale

another time scale t_{sh} ~ shock life time

Acceleration time scale and maximum energy

- The highest energy is decided by the acceleration time scale.

$$\Delta t = \frac{3s}{s-1}\frac{\kappa(p)}{u_{sh}^2}\frac{\Delta p}{p}$$ Drury (1983)

$$\kappa(p) = p^{\alpha} = \kappa(p_0)(\frac{p}{p_0})^{\alpha} = \kappa_0(\frac{p}{p_0})^{\alpha}$$

Define p0 $$\frac{3s}{s-1}\frac{\kappa_0}{u_{sh}^2}\frac{1}{\alpha} = t$$

If $\lambda \sim p^{1/3}$, $\alpha = 4/3$.

$$p_i << p_0, \qquad p_f = p_0,$$

$$p_i \sim p_0, \qquad p_f = 2^{1/\alpha} p_0,$$

$$p_i >> p_0, \qquad p_f = p_i$$

$$t = \frac{3s}{s-1}\frac{\kappa_0}{u_{sh}^2}\frac{1}{\alpha}(\frac{p_i}{p_0})^{\alpha}[(p_f/p_i)^{\alpha} - 1]$$

$$(p_0/p_i)^{\alpha} = [(p_f/p_i)^{\alpha} - 1]$$

$$p_f/p_i = (1 + (p_0/p_i)^{\alpha})^{1/\alpha}$$

p0 defines the highest accelerated momentum when the injection momentum is small. p0 is decided by the acceleration time scale.

Role of the preceding shock

- Assume a first shock accelerate particles from, say 10 keV to 10 MeV.

Expect the second shock, to only accelerate particles of 10 MeV to 20 MeV or so, *if the acceleration time scales are the same*.

- Expect the (integrated) intensity of energetic particle remains the same order of magnitude if the seed population is similar .

The higher intensities at high energies when there are preceding shocks ---> smaller acceleration time scale and more seed population at the 2nd shock.

Smaller acceleration time scale:

$$\boxed{\Delta t = \frac{3s}{s-1}\frac{\kappa(p)}{u_{sh}^2}\frac{\Delta p}{p}}$$

➔A smaller κ at the second shock.

A decrease of k by 10 --> an increase of 32 for the maximum kinetic energy.

Increased seed population:
May be a smoking gun from observations.

Spectrum after the second shock

Assuming a spectrum of $f(p) = p^{-\gamma}$ $p_1 < p < p_2$ after the first shock,

What is the spectrum g(p) after the second shock?

Consider particles in (q, q+ dq), after the passage of the second shock:

$g(p,q) = c(q)p^{-\beta}$ $q < p < p_{max}(q)$ $p_{max}(q) = q(1+(q_0/q)^{\alpha})^{1/\alpha}$ $\beta = 3s/(s-1)$

Number conservation: $c(q) = [\beta - 3/(q^{3-\beta} - p_{max}(q)^{3-\beta})](q)q^{2-\gamma}dq$

Integrate over q: $$\boxed{g(p) = \int_{p1}^{p2} \frac{(\beta-3)q^{2-\gamma}}{q^{3-\beta} - p_{max}(q)^{3-\beta}} dq \quad p^{-\beta}}$$

Special case: $t -> \infty$ $p_{max}(q)^{3-\beta} -> 0$

$$g(p) = \frac{\beta - 3}{\beta - \gamma}(p_2^{\beta-\gamma} - p_1^{\beta-\gamma})p^{-\beta}$$

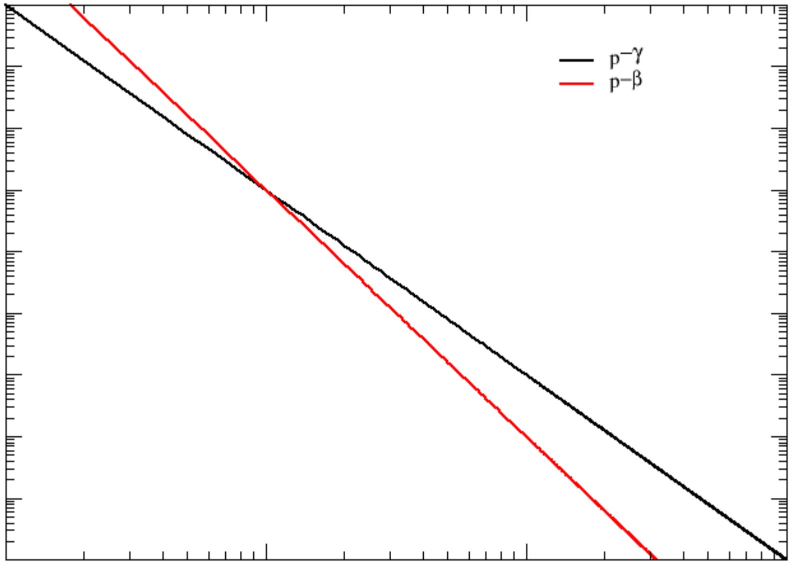
Two cases

- β>γ

spectrum does not change

$$f(p) = p^{-\gamma} \quad p_1 < p < p_2$$

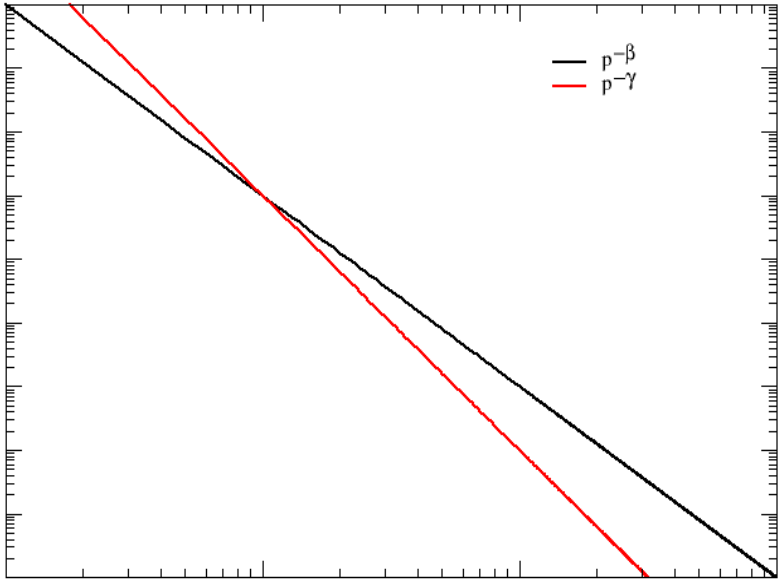
$$g(p)/f(p) = \frac{\beta - 3}{\beta - \gamma}$$



2) β<γ

Harder spectrum, dramatic increase of intensity at high energies

$$g(p)/f(p) = \frac{\beta - 3}{\gamma - \beta}(p/p1)^{\gamma-\beta}$$



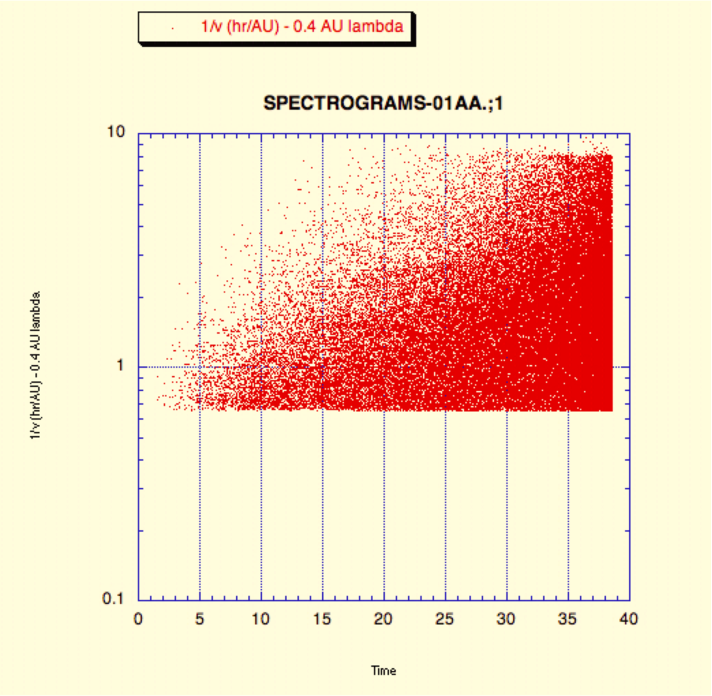
<u>The downstream magnetic turbulence at the preceding shocks decides the acceleration time scale at the 2nd shock!</u>

Possible signatures from observation (1)

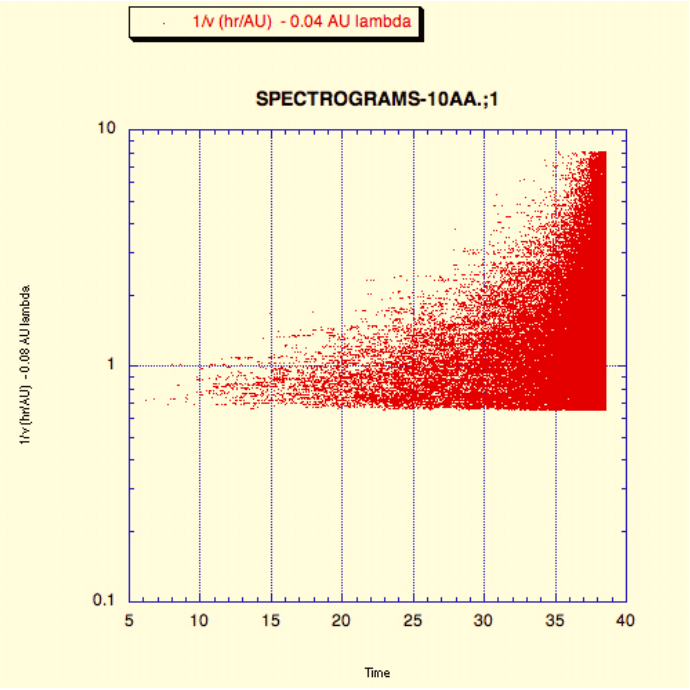
- Spectrogram– the story-teller: *(Li et al. in preparation)*

Particles escaped from the second shock will propagate in the turbulence-enhanced “downstream” region of the first shock.

Expect smaller mean free path.



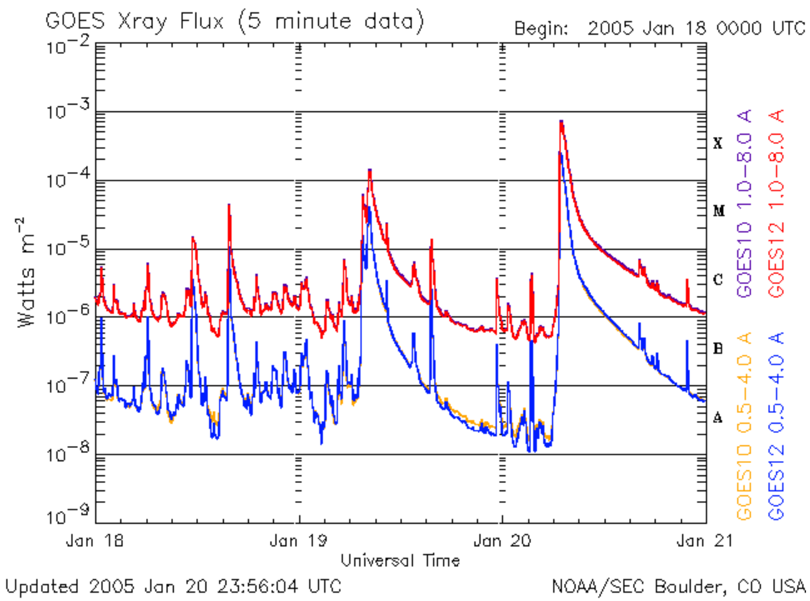
Less interplanetary scattering



More interplanetary scattering

Possible signatures from observation (2)

Enhanced seed population downstream of preceding shocks?



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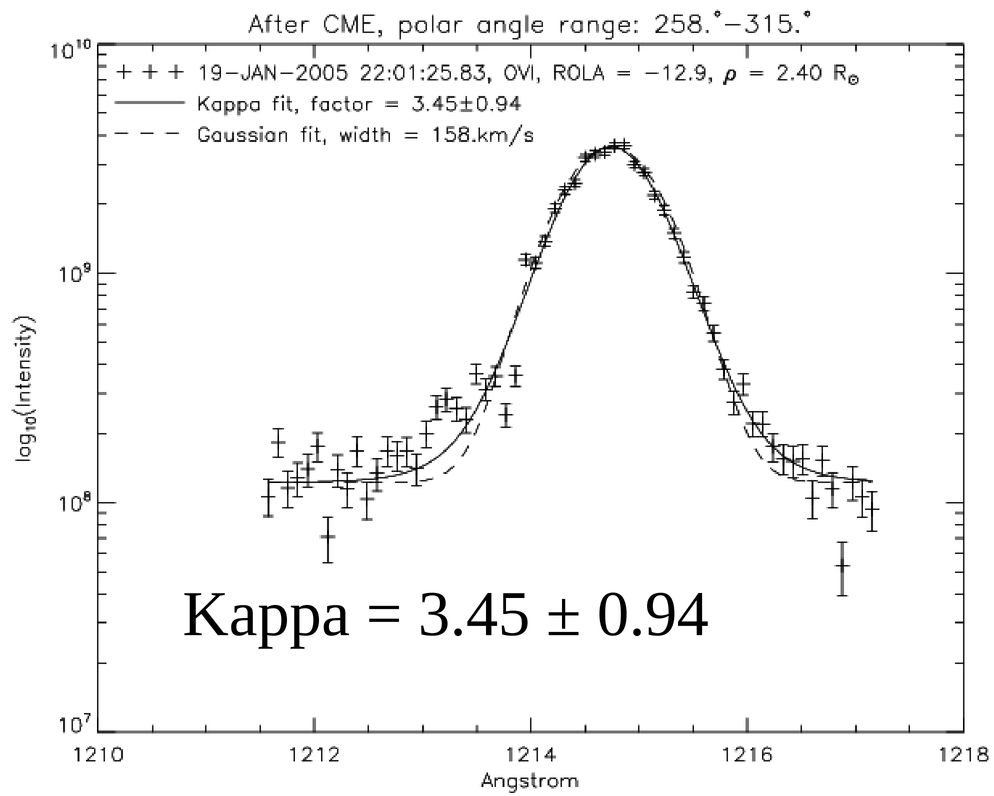

Kohl et al, private communication

non-Maxwellian!

- From event to event, distribution can vary dramatically. However, departure from Maxwellian is probably common.